NRL REPORT 3729

SOUND TRANSMISSION TO LONG RANGES IN THE OCEAN

R. J. Urick

September 6, 1950

Approved by:

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ABSTRACT

Recent use of half-second pulses at 7.4 kc for sound transmission measurements at ranges between 5 and 28 miles in the deep ocean has shown that sound can travel to such ranges by either or both of two paths. One path is by reflection from the bottom; the other is a channelled path lying within the near-surface wind-mixed layer and involving repeated reflections from the ocean surface.

The bottom reflection provides the only effective path between a source and receiver lying below the mixed layer. For this path the data indicate an absorption coefficient at 7.4 kc of 0.6 db per kiloyard, a figure about 40 percent smaller than expected from other measurements at higher frequencies.

The near-surface path is the result of sound trapping by the isothermal wind-mixed layer. That this trapping can be almost complete under some conditions is shown by evidence from the measurements that leakage out of the channel amounts to only 0.2 db per kiloyard. For a shallow source and receiver, mixed-layer sound channelling with the above value of attenuation coefficient accounts for a transmission excess of 30 db at 25 miles over what was anticipated on the basis of spherical spreading and the best available estimate of attenuation.

PROBLEM STATUS

This is an interim report on one phase of the continuing problem of sound propagation in the ocean.

AUTHORIZATION

NRL Problem S02-03R
NR 522-030

SOUND TRANSMISSION TO LONG RANGES IN THE OCEAN[1]

It is often stated that in sonar most of our troubles can be attributed to the medium. Since the ocean is in many ways the most uniform and homogeneous of all natural media, it still possesses many qualities (such as a low sound velocity, reverberation, and a rough surface) which present difficulties to sonar. Such natural limitations are in the broad sense no different from those encountered in other fields of applied geophysics, and we can do little else than to study these limitations and circumvent them as best we can. If one had to decide on which of the acoustic properties of the ocean is most important to sonar, the attenuation of sound in the sea would perhaps be given greatest consideration, since the amount of loss that has to be suffered by the out-going signal on its way to and from the target determines the degree of success of sonar detection.

The measurement of transmission losses in the ocean has a history dating back at this Laboratory at least 17 years, in an effort at that time to understand the vagaries of echo detection ranges in the years following World War I. Measurements continued in different ocean areas up to the beginning of the last war, and their principal achievement was the recognition of downward refraction in affecting sonar ranges. During World War II the two NDRC laboratories were active in this field, and an impressive body of knowledge was built up. Nearly all of the data consisted of transmission measurements between a shallow source and a shallow receiver at the frequencies and ranges then of practical interest to sonar. Some was obtained on transmission from a shallow source to a deep hydrophone and a little on transmission from a deep source to a deep hydrophone. At the present time, the hope for materially greater sonar ranges rests in part upon the use of lower frequencies and the ability to utilize natural sound channels. Transmission measurements at comparatively long ranges, for different combinations of depths, and at lower frequencies than in the past, are accordingly of immediate practical significance.

Such measurements have been the objective on three field trips totalling about 30 operating days during the past year. Field work on the last of these trips was completed in March 1950. However, by way of introduction, Figure 1 shows an example of the type of data obtained during the summer of 1949 on a cruise between New London, Bermuda, and Cape Hatteras.[2] CW transmission measurements at 7.5 kc were made with the use of a projector that could be lowered from one surface ship to a specified depth, in conjunction with a number of hydrophones at a number of depths between 15 and 400 feet suspended from another surface ship.

1. Adapted from a paper presented at an NRL Symposium entitled "Sound Transmission at Long Ranges in the Ocean," May 17, 1950

2. Urick, R. J.,"Sound Transmission Measurements in the Long Island - Bermuda Region," NRL Report 3630, Confidential, Jan. 1950

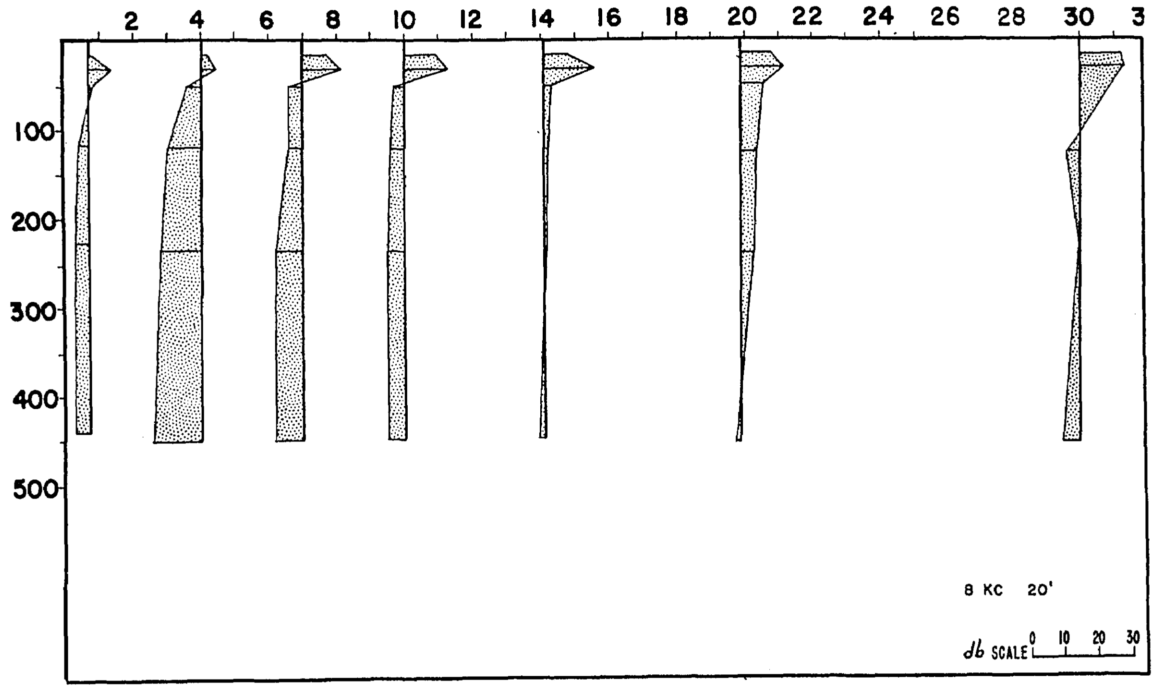


Figure 1 - Example of reduced transmission data obtained between New London and Bermuda, 1949

Measurements for various depth combinations were made at various fixed ranges. In Figure 1 these are indicated by a vertical line at each range. The measured levels were reduced by comparing them with a reference level which assumed spherical spreading and with the best guess as to the correct value of attenuation coefficient at this frequency (7.5 kc). The difference between this reference value and the measured value is plotted in Figure 1 on a db scale (shown at the lower right corner). If the measured level happened to be greater than the reference level at that range, the difference is drawn to the right. Thus, lines and areas to the right represent regions of signal level in excess of what there would be in a uniform ocean having the expected value of attenuation. Figure 1 was obtained for a projector depth of 30 feet; other plots were obtained at 16 kc and for other source depths and locations. Two things about Figure 1 are worth mentioning. One is the general deficiency of signal level at depths below a hundred feet at ranges of less than 10,000 yards, just at the ranges that present sonar is capable of reaching. This deficiency of signal can be attributed to downward refraction and to shadowing by the ocean's surface. This deficiency, however, becomes less as the range increases, until at a range of 30 kiloyards the level is the same as the free field level with attenuation. At shallow depths, there are signal excesses at all ranges, and these also increase as the range increases. These positive values at shallow depths with a shallow source can be attributed to sound-channelling in the wind-mixed surface layer. The increase of relative level with range may be due to one or more of several factors: an incorrect value of attenuation coefficient, an increasing addition of bottom-reflected sound as the range increases, or forward scattering by whatever the scatterers are that cause volume reverberation.

In order to understand better what is going on, the use of pulses instead of CW is desirable, for by this means we can achieve time separation of sound travelling by different paths. During a three-week period in February and March 1950, half-second pulses at a frequency of 7.4 kc were employed for transmission measurements in deep water off Guantanamo Bay, Cuba.

The reduced field data is given in the Appendix. Figure 2 shows some examples of the records obtained. These are on two-channel Brush recorder tapes, with acoustic signals on the upper portion, and simultaneously emitted radio pulses, plus one second chronometer ticks, on the lower. Four such records appear in the figure, one for each of four hydrophone depths for a source depth of 30 feet. The water depth was 2500 fathoms, which happens to be about the mean depth of all the oceans of the earth, and the bathythermograms showed a mixed layer averaging 260 feet in thickness overlying a sharp thermocline. The records have been aligned with a radio signal at the left. Inspection will show that two pulses, labeled D and B, are received for every one sent out. By careful measurement of time intervals, the pulse labeled D can be identified as the one travelling near the surface in a more or less direct line, and the B pulse as the reflection from the bottom. Identification of associated radio and sound pulses was made possible by the use of irregular time intervals between pulses. The travel time, incidentally, for a one-way path 44,700 yards in length is about half a minute. These four records are for a shallow projector and hydrophone combination, for a number of ranges.

Figure 3 shows some records at a fixed range of 25,000 yards and a source at 30 feet, for a number of hydrophone depths. It should be noticed how the amplitude of the bottom reflection, labeled B, remains fairly constant as the hydrophone depth is changed. Comparison should be made with the scale of db relative to constant arbitrary reference at the right of each record. This independence of bottom reflection on depth combination is what would be expected, since near-surface thermal and velocity gradients have little effect on sound travelling at an appreciable angle to the horizontal. By contrast, notice how the direct pulse, D, becomes weaker as the receiver depth is increased. Near the surface, the D pulse is many times stronger than the bottom pulse; but at a depth of 363 feet it is almost absent from the record. This is all for a source at the thirty-foot depth. By reciprocity we should expect the same sort of thing for a hydrophone at 30 feet or so, and for a variable depth of source. Figure 4 shows a number of records of this type for 3 source depths of 30, 200, and 350 feet and for a hydrophone at 15 feet. It is seen here also that the D pulse weakens with depth, but not to such an extent as when the receiver, instead of the source, is lowered.

One additional point concerning the shape of the pulse at these ranges is worth mentioning, at least to the extent that it can be recorded by the Brush pen-and-ink recorder. Whenever the direct pulse is strong enough to stand out above noise, it has straight sides and is of the same length as at short range. That is to say, even at 55,000 yards (the maximum range reached) as well as at 25,000 yards, the direct pulse as shown in this figure is not broadened into a long blob but maintains its integrity. This feature has importance in its effect on target recognition. The bottom signal is, however, broadened out and broken up, presumably because of a rough bottom and a very broad beam from the projector. To make the story complete, Figure 5 shows records from a deep source at a depth of 350 feet for four hydrophone depths. It should be noticed that the two signals have about equal amplitude except when the hydrophone is also deep, in which case the direct signal is gone altogether. As before, the bottom pulse is unaffected by hydrophone depth. The indication is, therefore, that in echo-ranging in order to reach a target believed to be in the thermocline, or at least below the mixed layer, it is better as far as getting sound out to the target and back again is concerned, to utilize the bottom reflection and to employ downward-directed sound. Using the bottom-reflection for echo-ranging on a deep distant target will, however, bring up new problems in search procedure and target detection amid surface and possibly bottom reverberation.

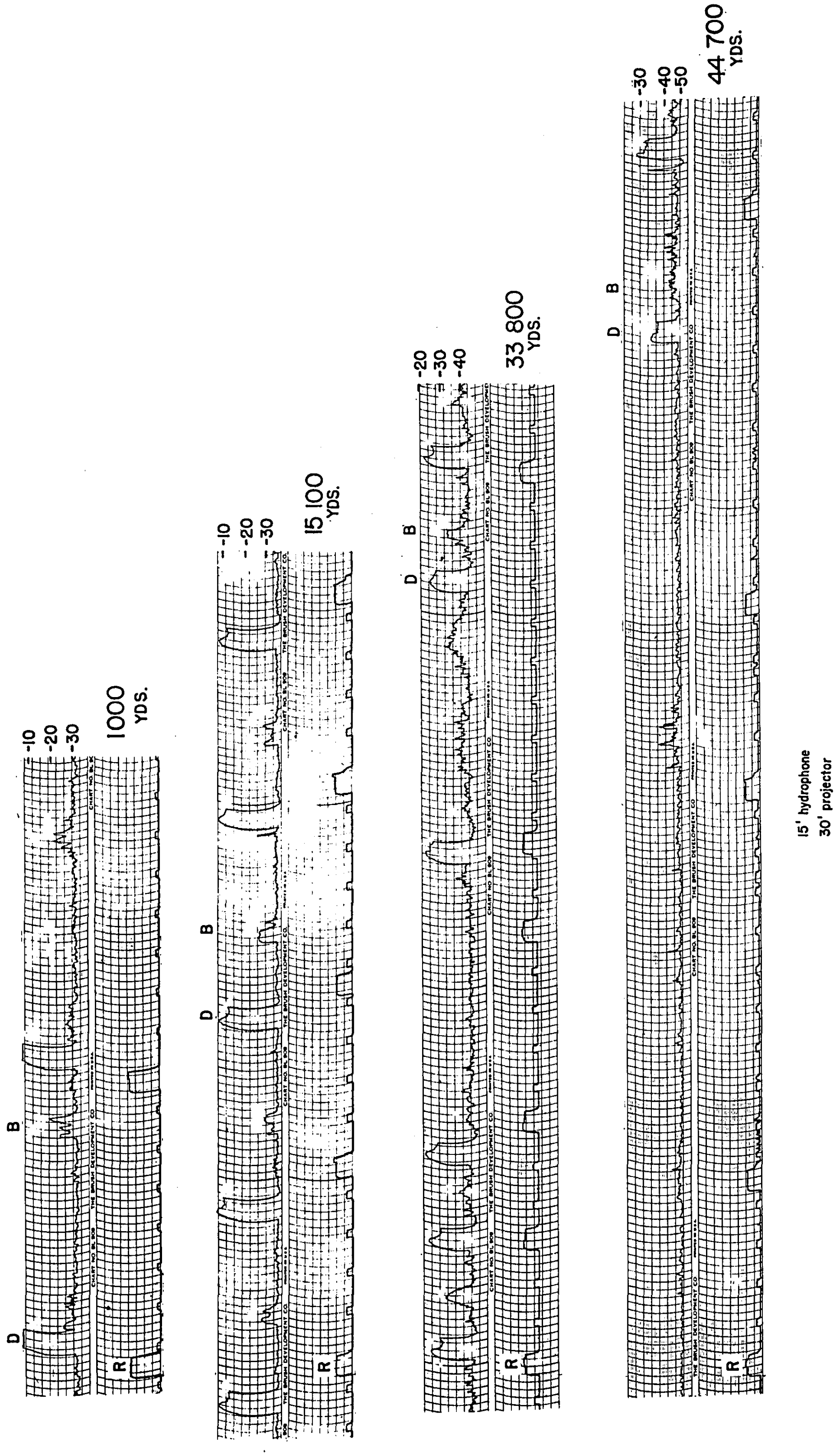


Figure 2 - Examples of records obtained at four ranges, with hydrophone at 15 feet and projector at 30 feet

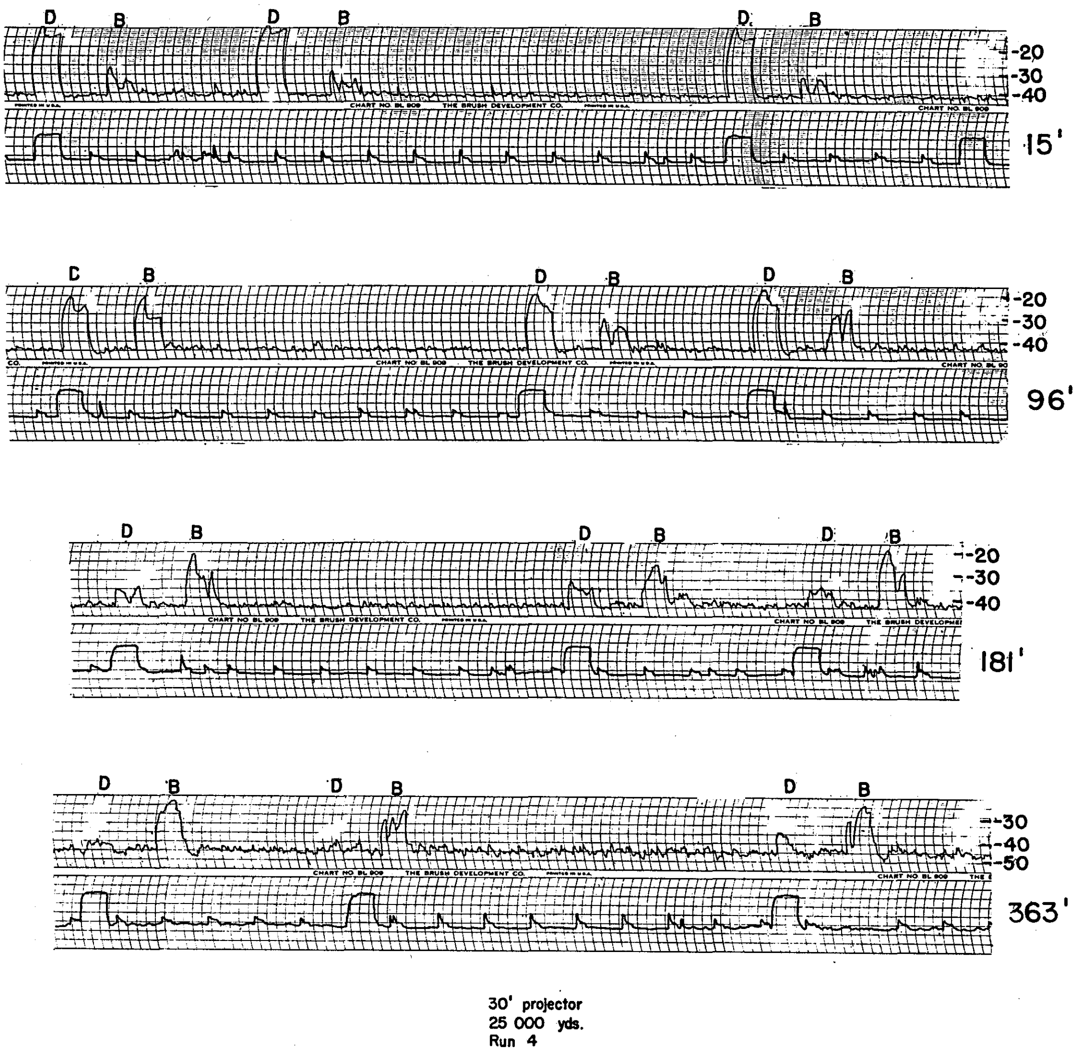


Figure 3 - Examples of records for four hydrophone depths, at 25,000 yards range and projector depth at 30 feet

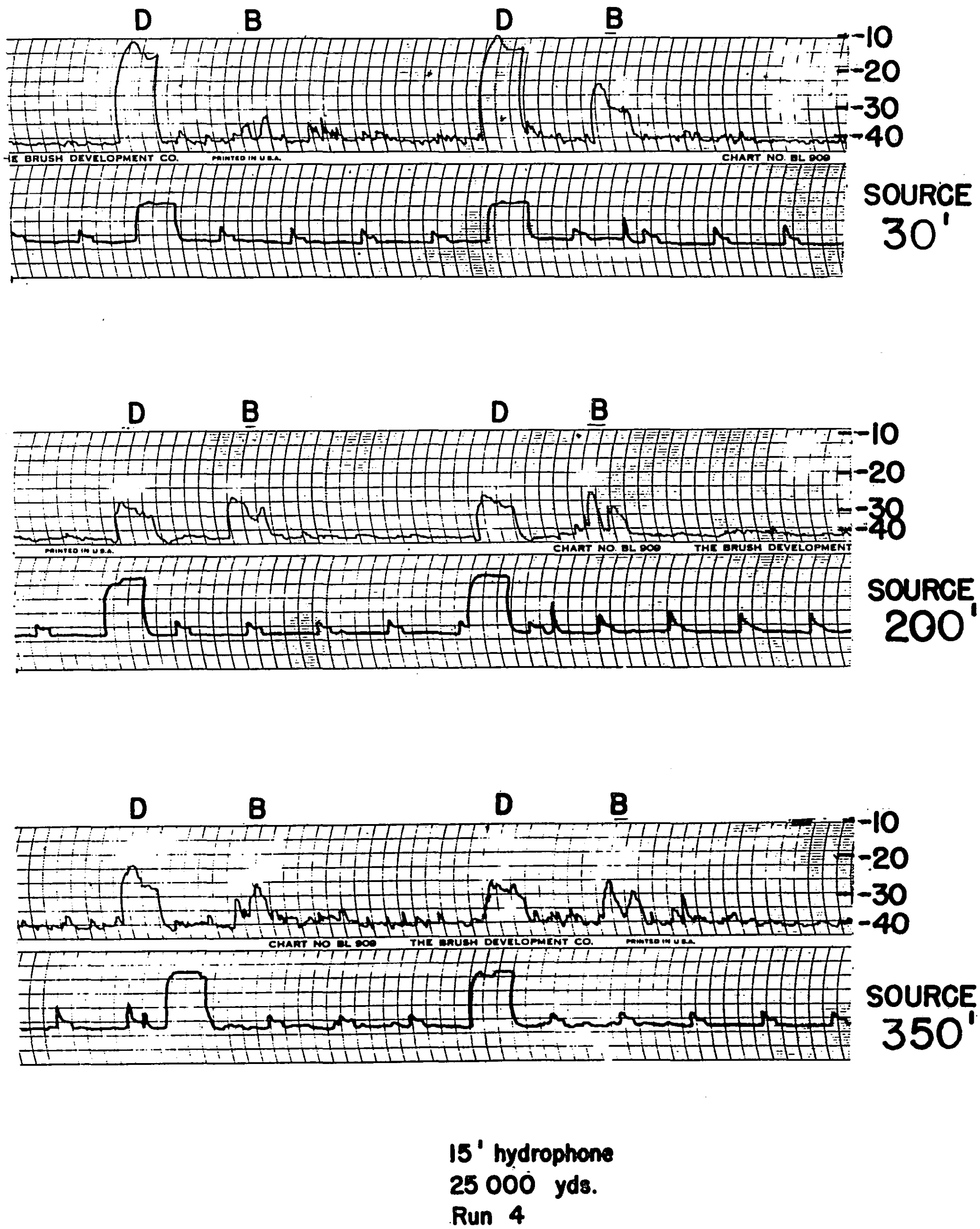
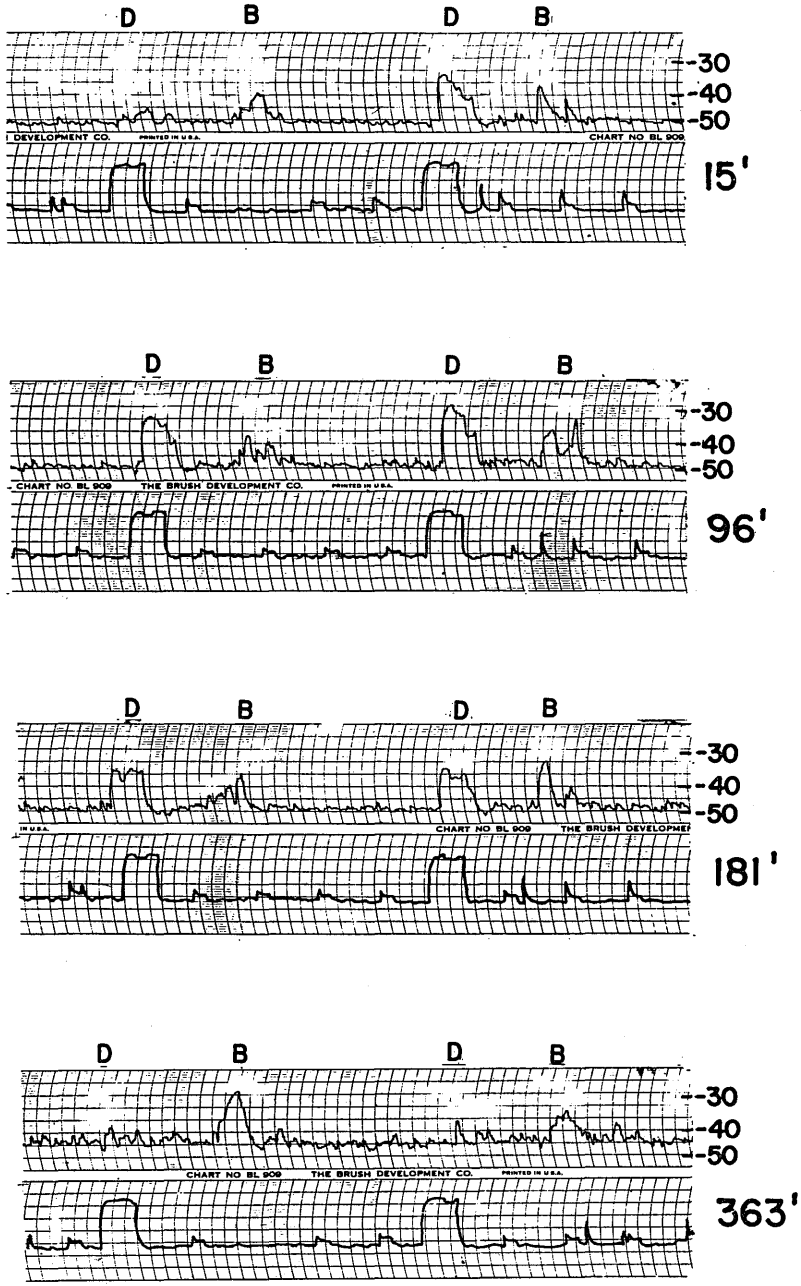


Figure 4 - Examples of records for three source depths, at 25,000 yards range and hydrophone depth at 15 feet



350' projector
25 400 yds.
Run 4

Figure 5 - Examples of records for three hydrophone depths, at 25,400 yards range and projector depth at 350 feet

Let us now turn to a consideration of transmission losses. Figure 6 shows as points the average measured transmission losses for a shallow source and a shallow hydrophone. Dock-side measurements at short range at the end of each day's work permitted the conversion of signal level to transmission loss, shown in Figure 6 as signal level relative to its level at one yard. The solid curve is computed on the assumption of spherical or three-dimensional spreading together with an attenuation coefficient of 1 db/ky. This figure of 1 db/ky was obtained by extrapolation down to 7.4 kc of minimal attenuation coefficients measured by others at higher frequencies. The observed signals are seen to be in excess of the curve by as much as 30 db at a range of 25 miles.

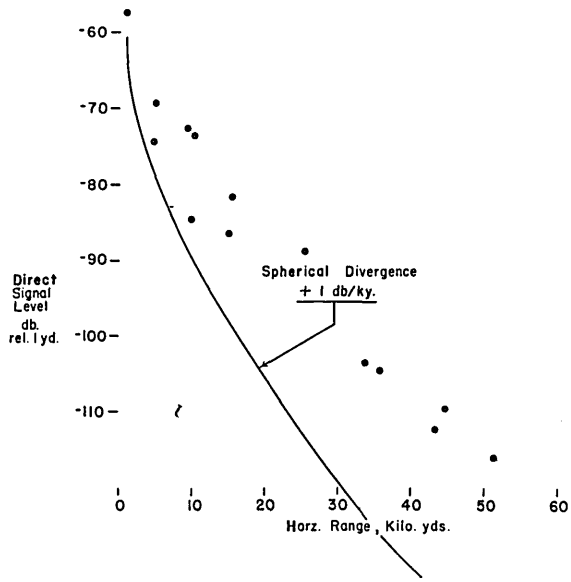


Figure 6 - Measured transmission losses for the direct signal vs. range, with projector at 30 feet and hydrophone at 15 feet

A transmission loss can be considered to be made up of the several parts: Divergence loss, attenuation loss, and refraction loss. Divergence loss is due to uniform spreading in one or two dimensions, and represents a necessary weakening of signal as sound spreads out from the source and insonifies a greater and greater volume of ocean. What can be somewhat redundantly called an attenuation loss is due to scattering by small particles and irregular surfaces, and by conversion into heat through the processes of viscous and relaxation absorption. Refraction loss represents spreading that is not uniform because of thermal gradients, focussing, shadow zones, variations in intensity in sound channels, and so on. It may be a negative loss if any sort of focussing is present. It accounts for much or all of the scatter of measured data from a smooth curve, as shown in Figure 6. If we are interested for the most part in average or smoothed values, which constitute a first approximation toward explaining measured losses, this term may be neglected. At long range one feels intuitively that this loss may be small, since sound in travelling long distances has had time, so to speak, to be distributed in space in a more uniform manner than it is at short ranges. At any rate, if this last term be neglected, we can write an expression for the transmission loss as $N \log R + \alpha R$ where α is normally called the attenuation coefficient expressed in decibels per kiloyard, and N is a number which for spherical spreading is 20 and for cylindrical or two-dimensional spreading is equal to 10. A third and important type of spreading to be discussed later involves spherical divergence out to a certain range and cylindrical beyond.

In attempting to fit observed transmission data in such a fashion there are therefore two constants at our disposal. The correct evaluation of these constants is of more than academic interest, since they obviously provide valuable information as to the transmission processes that operate in the ocean. Any determination of attenuation coefficient is dependent, therefore, on what sort of spreading law is believed to hold. At the higher sonar frequencies, where short-range runs suffice for the determination of the coefficient, the assumption that the spreading is spherical will be reasonably close to the truth. But as transmission runs are made at lower and lower frequencies, it is necessary to go to greater and greater ranges, and the separation of spreading and attenuation coefficients becomes more troublesome, especially for CW measurements where direct and bottom reflected sound are intermingled.

The use of bottom-reflected sound alone, however, permits a determination of attenuation coefficient by making the reasonable assumption that spherical spreading applies to a path involving a single reflection from the bottom. Then, turning to the direct signal, we can use this determination of the coefficient to determine the type of spreading which applies to the near-surface path.

The upper portion of Figure 7 shows signal level plotted against range for the B pulse of the Guantanamo data after correction for directivity of projector and hydrophone. All pulses for every depth combination at a particular range were averaged to give a single point at that range. The three curves are for spherical spreading with three different values of attenuation coefficient.

We see that the measured points fall fairly well on one of the family of computed curves, the one having an attenuation coefficient of 0.6 db/ky. Another way to arrive at this evaluation is shown in the lower half of Figure 7, where the excess loss over the spherical-divergence loss is plotted against range. A straight line through the origin with a slope of 6/10 db/ky gives a reasonable fit to the data. The fact that the line passes through the origin indicates that the loss on reflection from the bottom is small, at least within the limits of accuracy of this data. Since the reflection coefficient at the bottom probably increases with range (that is, as the angle between the path and the bottom decreases), one would expect the attenuation coefficient determined in this manner to be somewhat too low, although not by very much since the line matching the data passes through the origin.

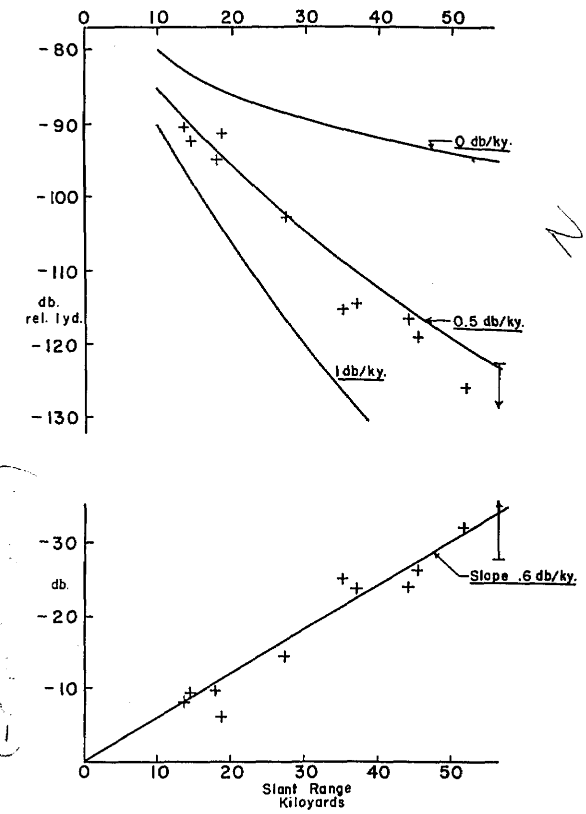


Figure 7 - Transmission loss, plotted as signal level, for the bottom-reflected (B) pulse

Figure 8 shows different guesses as to the manner in which attenuation varies with frequency. These are algebraic curves, which, at the time they were drawn, were believed to best represent existing measured data. The upper function was obtained by Dr. E. B. Stephenson from field data obtained in 1937 and 1938; the lower pair of curves are most recent in origin. All are based on data obtained at frequencies of 15 kilocycles or more, and even here some of the values reported in the literature probably are suspect because of the improper use of spherical divergence in the reduction. In the octave 5 to 10 kc the curves are extrapolations from higher-frequency measurements. The dot representing the present determination at 7.4 kc is 30 or 40 percent smaller than had been anticipated.

Let us now consider the direct or near-surface path taken by the D event. On the left side of Figure 9 is drawn the bathythermogram that prevailed in an essentially constant manner in the Guantanamo area during the period the measurements were taken. Converting

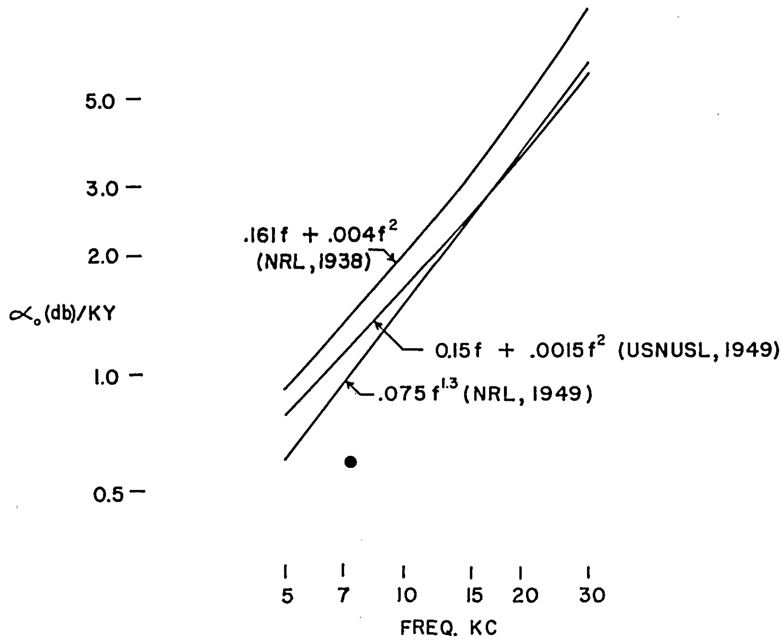


Figure 8 - Empirical absorption - frequency functions. The dot shows the present determination at 7.4 kc.

temperature and pressure into sound velocity, we obtain the curve shown on the right. Below the surface is a layer of increasing velocity down to a depth of 260 feet; the total increase in refractive index as shown by the arrows amounts, however, to only a little less than one-tenth of one percent. This increase indicates the presence of a sound channel, which has its axis, or depth of minimum velocity, at the surface, and which tends to contain within itself sound which originates within it and thus prevents the escape of energy to great depths. For radio waves, this situation is well known as trapping by a ground-based duct, resulting in nonstandard propagation. Figure 10 shows a ray diagram corresponding to this bathyvelogram. The upward-curving rays in the channel reach great ranges by repeated reflections from the surface. At each reflection some energy is lost to the channel by reflection and scattering from the rough ocean surface, as well as by diffraction from the base of the channel. A target below the channel at a great distance from the source receives sound primarily from the bottom, but also through leakage out of the channel along a path remaining in the channel for most of the distance from the source. A target in the channel receives energy not only by way of the bottom, but also along the many channel rays between source and target, although travel times along the extreme rays differ by only a few milliseconds at 20 miles.

Now in the case of a channel we might expect substantially cylindrical spreading as shown in Figure 11 beyond a range where the sound from the source can be said to "fill up" the channel. At great distances from the source there is a zone of cylindrical spreading; at short distances from the source there is a region of spherical spreading where the emitted sound is still spreading in three dimensions; in between is a transitional zone where neither of the simple spreading laws apply. The distance r_0 is in effect the range within which the channel sound spreads spherically and beyond which it spreads cylindrically. It can be computed in the following manner. Suppose we have a nondirectional source of power output P. Providing θ is small, the power radiated into the channel is P times θ, where θ is the angle between the limiting rays trapped in the channel. The smallness of θ

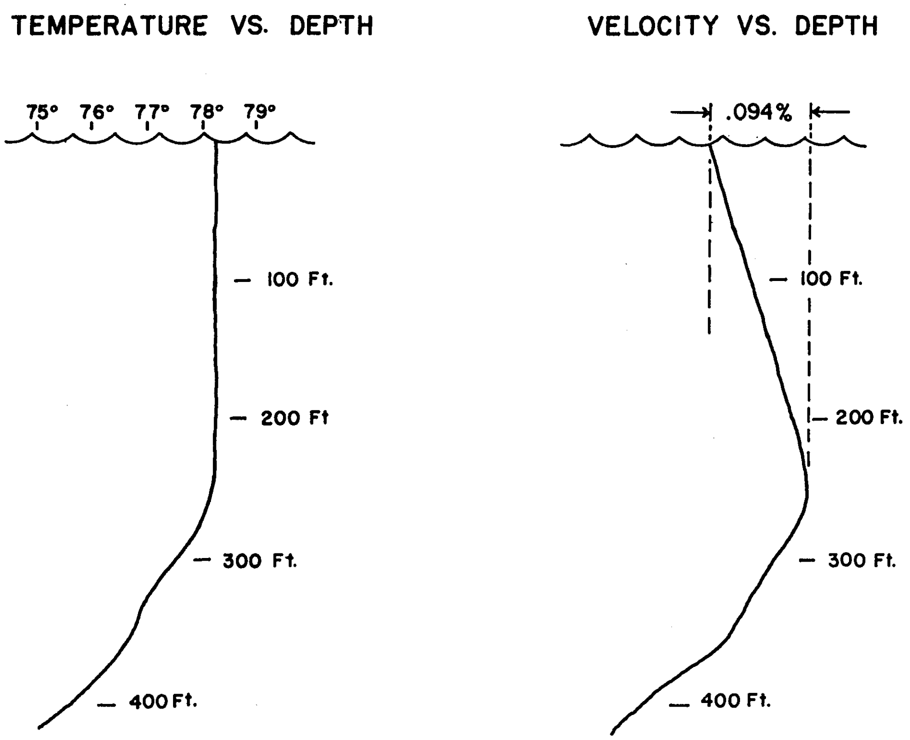


Figure 9 - Typical bathythermogram and computed velocity depth curve

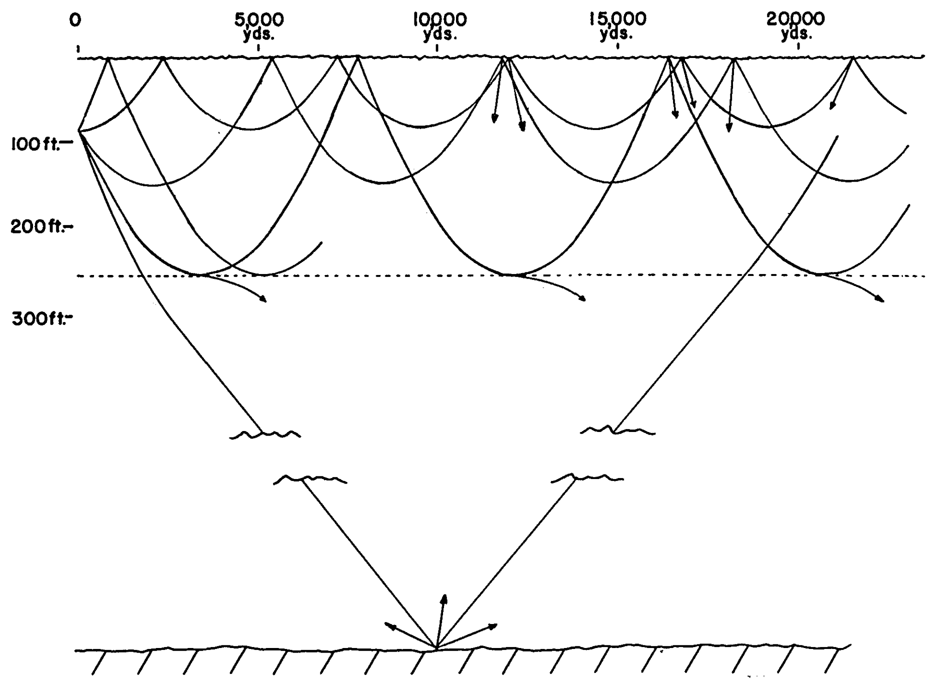
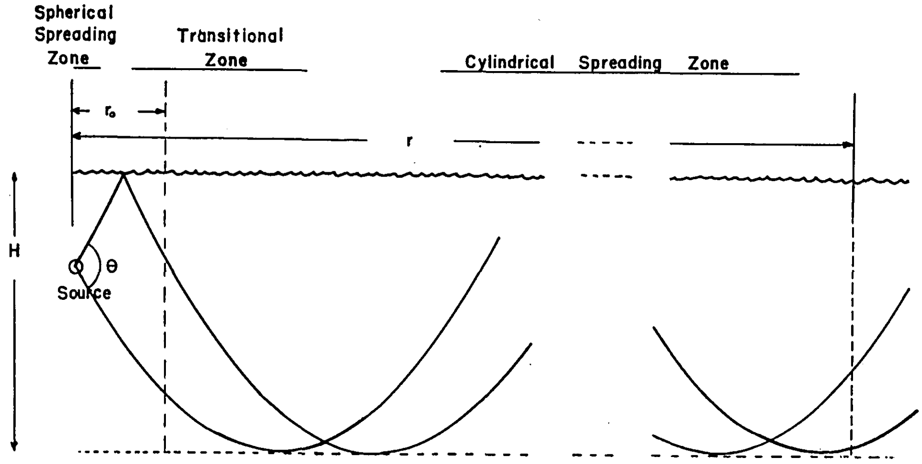


Figure 10 - Ray diagram, showing surface-channelled and bottom-reflected paths



POWER RADIATED INTO CHANNEL = $P\theta$

AVERAGE INTENSITY AT RANGE $r = P\theta/2\pi rH = P/2\pi rr_0$

$r_0 = H/\theta$

FREE-FIELD INTENSITY = $P/2\pi r^2$

GAIN OF CHANNEL = r/r_0

Figure 11 - Average intensity and gain of a sound channel

and of all the angles in these ray diagrams should be remembered. This amount of power is distributed in some manner at range r over a cylindrical surface of area $2\pi rH$, where H is the thickness of the channel. That is, the average intensity is $P\theta/2\pi rH$. If now we write H/θ as r_0, we have $P/2\pi rr_0$. If we write the denominator as $2\pi r_0^2\, r/r_0$ we may observe that r_0 is indeed the spherical spreading distance. Since for isothermal water θ is simply related to H, we observe that r_0 depends only on the thickness of the mixed layer; for a water temperature of 75^0, r_0 is 66 times the square root of the thickness in feet. For the Guantanamo data, where H was 260 feet, r_0 is about a thousand yards.

To obtain an idea of how effective a channel can be, we may compare this average intensity with the intensity which would be present if the channel were absent, and an isovelocity condition with straight-line propagation prevailed. Then the intensity is $P/2\pi r^2$, and the ratio of intensities with and without the channel is then r/r_0. This may be conveniently called the "gain" of the channel. As an example, at a range of 20,000 yards or 10 miles when r_0 is 1000 yards, the gain is 20, or 13 db. Now this is the maximum gain that could be expected from the channel in the absence of leakage of energy out of the channel; with a rough surface and nonuniform thermal conditions we would expect to find somewhat less than this, depending on sea state and conditions at the base of the channel.

Figure 12 shows two computed loss curves together with the same measured average levels plotted in Figure 6 for the first or D pulse under the combination of a 30-foot source depth and a 15-foot hydrophone depth. The upper curve was computed using a mixed-layer thickness of 260 feet to find r_0 as 1060 yards, and an absorption coefficient of 0.6 db/ky determined from the bottom reflection data. Also shown is a curve using 0.8 db/ky instead of 0.6, with which the measured points are in better agreement. This excess attenuation of 0.2 db/ky may be reasonably attributed to leakage of energy out of the channel, perhaps due, for the most part, to the roughness of the sea surface. Sea states 1 or 2 prevailed during the measurements. Even with leakage, the gain of this channel is about 10 db between 20 and 50 kiloyards.

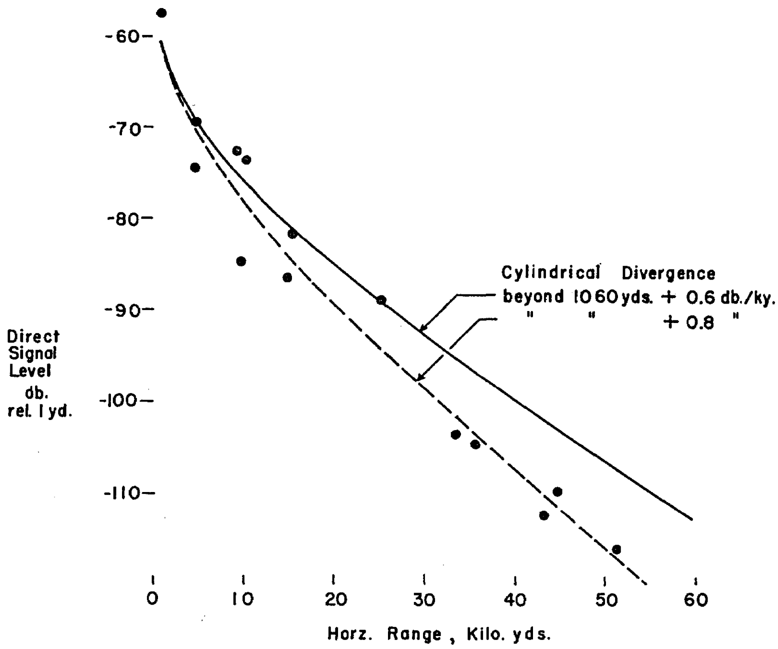


Figure 12 - Transmission losses of Figure 6 compared with computed loss curves with and without channel leakage

Let us now generalize and write the following expression for the transmission loss at long ranges in sound channels:

$$20 \log r_0 + 10 \log \frac{r}{r_0} + \left(\alpha + \alpha_L\right) r.$$

The first term is the loss in db due to spherical spreading to range r_0. The second term, $10 \log r/r_0$, represents cylindrical spreading beyond r_0 to the range r. The last term is an attenuation loss, proportional to the range r, having two coefficients. The first is an absorption coefficient which can be determined from bottom reflection data with the assumptions that the reflection coefficient does not vary greatly with incident angle over the range used, and that the absorption at all depths in the ocean is the same. These are points on which further research is needed. The second coefficient, α_L, takes care of incomplete trapping and represents the effect of leakage out of the channel. It may be expected to vary with sea state and with channel thickness, being greater for rough seas and thin channels.

In fact, an analysis of the data at hand does indicate a dependence of α_L on sea state, although a good deal more data is needed to formulate this accurately. Figure 13 shows the results (based on the above expression) of an analysis of the 1949 data,[1] for which a variation in wind force and sea state occurred, for the combination of shallow source and receiver. It shows a definite tendency for α_L to increase with increasing wind force. At each reflection of a ray from a rough surface, some energy will be reflected and scattered at angles different from the angle of incidence with the horizontal. This sort of "beam pattern" of the surface reflection will widen as the roughness of the surface increases, and more of this reflected energy will be lost to a thin channel than to a thick one.

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[1] Urick, op. cit.

This inverse dependence of α_L on the thickness of the mixed layer may account in a large part for the well-known generalization that sound conditions are better when the mixed layer is thick. When α_L is large the gain of the channel can easily become less than unity, that is, the transmission is worse with the channel present than if it were absent. Channelling with large α_L keeps the emitted sound close to the surface, where it is constantly weakened by surface scattering. The above formula yields the average intensity in the channel, and is useful for predicting the loss when the target depth, although believed to be still in the channel, is unknown. A more complete formula would give the average loss for a particular depth combination of source and receiver.

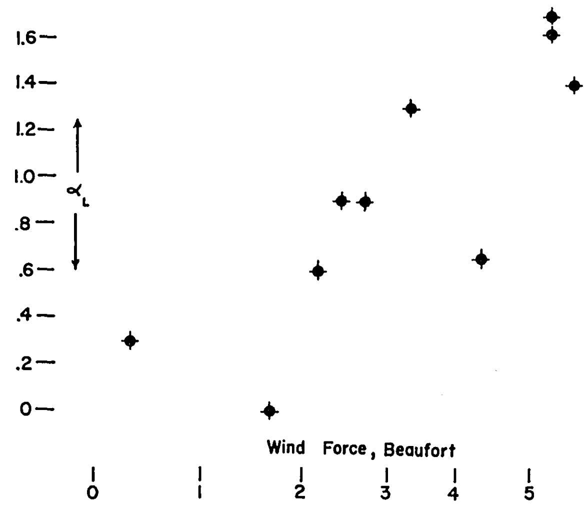

Figure 13 - α_L in db per kiloyard vs. wind force for the New London-Bermuda data of NRL Report 3630 of 1949

As was seen from the examples of Figures 2 and 5, the direct or channel signal becomes weaker as the hydrophone depth increases. Figure 14 shows this quantitatively for three depths of source. The 30-foot source depth is not far from the axis of the channel, that is, the surface; the 200-foot depth is near the base of the channel, and the last depth is below the channel in the thermocline. The difference in decibels in direct signal level is plotted against depth, averaged over all ranges between 5,000 and 50,000 yards relative to a hydrophone at a depth of 15 feet. It will be observed that the direct-signal level falls off as a hydrophone is lowered, although this depth dependence seems to diminish as the source depth becomes greater. The best transmission is obtained with both source and receiver near the surface, and the transmission deteriorates as either or both ends of the path are removed from the axis of the channel. However, no data have been obtained shallower than 15 feet in connection with the observation reported by the KAYO groups that listening ranges are improved for a hydrophone just below the surface.

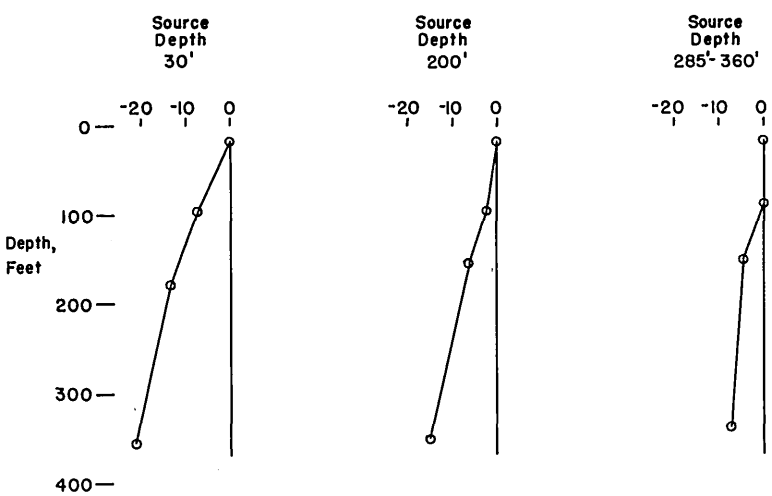

Figure 14 - Variation of level, relative to that at 15 feet, in the surface sound channel, for three depths of source

One other qualitative observation that was made from the records was that for some depth combinations the bottom reflection was stronger than the direct signal, and vice versa. Figure 15 shows the average difference in decibels between these two signals plotted against hydrophone depth for three depths of source. When the bottom-reflected pulse is greater, the difference is shown as positive, to the right. When the direct signal is the greater, the difference is plotted to the left. As mentioned before, the transmission loss for the bottom-reflected path at 7.4 kc is given by using spherical divergence for the slant distance plus this distance times 0.6 db per kiloyard. The combination at the upper left with both source and receiver shallow represents the optimum sound channel condition, and it is seen that the near surface or direct signal is here greater than the bottom signal. At the lower right, when both source and receiver are deep, the bottom reflection is much the stronger because the direct signal can be transmitted to long ranges only by leakage into and out of the channel. At the lower left and upper right we have the combination of one end of the path in the channel and one out, and in this case it is seen that here too the bottom reflection is somewhat the stronger. The middle plot is for the source in the channel but near the base of it, where its effectiveness is much less, and we observe that for a hydrophone in the channel the two signals are about equal; but that when the hydrophone is below the channel, as might be expected, the bottom signal is much the greater.

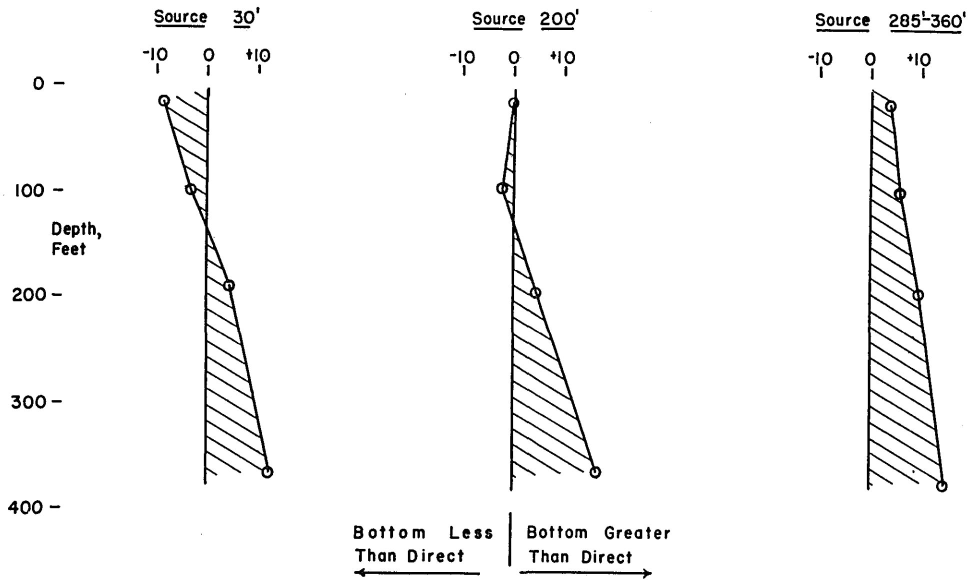

Figure 15 - Average difference in db between bottom-reflected and direct-path signal for three source depths. Ranges 15,000 to 51,000 yards averaged

If a generalization be permitted, the practical significance of this is that, for a surface or schnorkelling target when a thick mixed-layer is present, it is advantageous to employ the ordinary or near-surface path at long ranges. If for any reason the target is believed to be deep, it is desirable, as far as getting sound out to the target and back again is concerned, to rely on the bottom reflection. It seems certain that the long listening-detection ranges that have been observed on deep targets have in fact been due to the bottom reflection. Echo-ranging by the bottom reflection will involve new problems that only actual field trials with suitable long-range equipment can solve.

In summary, the data obtained lead to the conclusion that the wind-mixed isothermal layer is remarkably effective as a sound channel, at least when it is relatively thick and the surface is not too rough. This recognition of sound trapping in the mixed layer is not new, for it was realized many years ago—not long after the first sound transmission runs were made. In the interim, the importance of channelling by the mixed layer had a tendency to be forgotten even though in radio-wave propagation trapping by even weaker ducts was recognized. Even if such channelling was admitted, its effects were considered unimportant because of the weakness of the upward refraction involved and the roughness of the surface. At any rate, the matter was of not too much practical importance as long as sonar echo ranges even under the best sound conditions were no more than 3000 or 4000 yards. The most optimistic estimates of transmission loss at long ranges were based on spherical divergence. Yet the Guantanamo data are an example of a case where leaky trapping improves transmission over the spherical spreading hypothesis by between 5 and 10 db depending on the range. In addition the absorption coefficient at 7.4 kc is apparently from these measurements appreciably smaller than was anticipated.

These conclusions are drawn from, and supported by, field work in just one area, at one time of year. The concepts presented as to processes and so forth should be regarded from a cautious scientific viewpoint as providing only working hypotheses to be verified or denied by additional field measurements. Such additional field work has been recently performed in the vicinity of Bermuda, and will be reported later. By the use of working hypotheses and a succession of field trips it is hoped to arrive at a better understanding of sound transmission to long ranges.

* * *

APPENDIX

The following table gives the reduced field data discussed in the text. The measurements were made in an area about 20 miles south of Guantanamo Bay, Cuba, in water of 2,500 to 2,600 fathoms depth, and are arranged in the table roughly in order of range.

Column 1 shows the "run" number, as used in the field, and the date.

Column 2 gives the time of day, in eastern standard time, for each group of data.

Column 3 is the range as determined from the radio-acoustic records for the "D" pulse, using the sound velocity of 1677 yds/sec corresponding to a surface temperature of 77°F as measured with the bathythermograph.

Column 4 shows the projector depth, and Column 5 the four hydrophone depths, as determined by means of depth gages attached to the projector and to the hydrophone string. No attempt was made to keep the hydrophones at strictly constant depth from run to run.

Column 6 is the average transmission loss, relative to one yard, of the direct or "D" pulse. The number of pulses shown in Column 7 were read and averaged to give the loss figure of Column 6. Dockside runs at ranges of a few yards were made at the end of each day's work; when corrected to one yard, they provided the reference for that day's data. When one or more pulses of a group were too weak to be readable, and so were buried by system noise, the following procedure was adopted. The level of the least readable signal was estimated, and this value was used for each unreadable pulse in computing the average; thus, the true average is in such cases less than the tabulated figure by a small, undeterminable amount. Where such unreadable pulses are less than half the total, the median transmission loss is also given, following the letters MED. The number of unreadable pulses is shown by the letter N; thus 7^{4N} means that of the 7 pulses available for averaging, 4 were below the least readable level. When signal plus noise, if readable, was only a few decibels greater than the noise background alone, a noise correction was applied. When more than half of the pluses in a group were unreadable, the transmission loss corresponding to the estimated least readable signal is given in the table, and the sign > is used to indicate that the actual loss is greater than the figure shown.

Columns 8, 9, and 10 apply to the bottom-reflected, or "B," pulse. The losses in Column 8 were computed in the same manner as those of the "D" pulse, except that a directivity correction for both projector and hydrophone was applied, as determined from directivity patterns obtained on the NRL sound barge. For this reason, no bottom-reflection data is given at the shorter ranges where the correction is great.

Column 9 gives the number of pulses used in computing the loss shown in Column 8, and Column 10 is the slant range in yards for this pulse as measured from the records, using a velocity of 1650 yds/sec for the average velocity over the deep path.

Column 11 gives the depth of the sound channel as read from the bathythermograms on making the correction for the pressure increase of sound velocity. Since the mixed layer in all cases was sharply defined, the channel depth is only slightly greater than the depth of the base of the mixed layer.

Column 12 shows the estimated sea state, and Column 13 gives the latitude and longitude of the receiving ship.

TABLE 1
Results of Tests, February and March 1950
Vicinity of Guantanamo Bay

1 Run and Date	2 Time (Est)	3 Horz. Range (Yds)	4 Source Depth (Ft)	5 Hyd. Depth (Ft)	6 Direct Signal Loss, 1 Yd (db)	7 No. of Direct Pulses	8 Bottom Signal Loss, 1 Yd (db)	9 No. of Bottom Pulses	10 Slant Range Bottom Refl. (Yd)	11 Depth of Channel	12 Sea State	13 Lat. & Long. of Recv. Ship
Run 5	0830	1006	30	15	57.2	22	--	--	--	200'	2	$19^{\circ}32'N$
2/24/50	"	"	"	83	58.3	15	--	--	--			$75^{\circ}11'W$
	"	"	"	155	67.5	18	--	--	--			
	"	"	"	334	67.4	8	--	--	--			
	0911	1057	200	15	62.8	13	--	--	--	210'		
	"	"	"	83	65.3	10	--	--	--			
	"	"	"	155	65.0	9	--	--	--			
	"	"	"	334	65.7	7	--	--	--			
	0924	1040	335	15	64.1	11	--	--	--	220'		
	"	"	"	83	60.2	13	--	--	--			
	"	"	"	155	62.4	11	--	--	--			
	"	"	"	334	65.8	9	--	--	--			
Run 1	1049	1220	30	15	48.6	25	--	--	--	270'	1	$19^{\circ}37.5'N$
2/17/50	"	"	"	110	--	--	--	--	--			$75^{\circ}32.5'W$
	"	"	"	222	--	--	--	--	--			
	"	"	"	420	--	--	--	--	--			
	1109	1220	200	15	--	--	--	--	--			
	"	"	"	110	64.8	24	--	--	--			
	"	"	"	222	--	--	--	--	--			
	"	"	"	420	74.5	12	--	--	--			
	1126	1200	380	15	63.9	10	--	--	--			
	"	"	"	110	63.9	13	--	--	--			
	"	"	"	222	--	--	--	--	--			
	"	"	"	420	61.6	11	--	--	--			
Run 5	0950	5030	30	15	74.3	27	--	--	--	230'	2	$19^{\circ}32'N$
2/24/50	"	"	"	78	84.4	22	--	--	--			$75^{\circ}11'W$
	"	"	"	146	87.8	16	--	--	--			
	"	"	"	322	87.2	28	--	--	--			
	"	4810	200	15	91.2	20	--	--	--			
	"	"	"	78	77.7	19	--	--	--			
	"	"	"	146	80.7	15	--	--	--			
	"	"	"	322	83.1	19	--	--	--			
			Repeat									
	"	4810	200	15	--	6	--	--	--			
	"	"	"	78	--	9	--	--	--			
	"	"	"	146	--	5	--	--	--			
	"	"	"	322	95.1	9	--	--	--			
	1030	4690	345	15	98.6	17	--	--	--	240'		
	"	"	"	78	97.0	16	--	--	--			
	"	"	"	146	96.0	12	--	--	--			
	"	"	"	322	88.0	23	--	--	--			
			Repeat									
	"	4690	345	15	99.0	2	--	--	--			
	"	"	"	78	97.5	2	--	--	--			
	"	"	"	146	96.2	4	--	--	--			
	"	"	"	322	--	3	--	--	--			
Run 1	1207	5030	30	15	69.2	11	--	--	--	270'	1	$19^{\circ}37.5'N$
2/17/50	"	"	"	110	78.2	17	--	--	--			$75^{\circ}32.5'W$
	"	"	"	223	80.5	6	--	--	--			
	"	"	"	421	92.2	8	--	--	--			

TABLE 1 (Continued)
Results of Tests, February and March 1950
Vicinity of Guantanamo Bay

1 Run and Date	2 Time (Est)	3 Horz. Range (Yds)	4 Source Depth (Ft)	5 Hyd. Depth (Ft)	6 Direct Signal Loss, 1 Yd (db)	7 No. of Direct Pulses	8 Bottom Signal Loss, 1 Yd (db)	9 No. of Bottom Pulses	10 Slant Range Bottom Refl. (Yd)	11 Depth of Channel	12 Sea State	13 Lat. & Long. of Recv. Ship
Run 1 2/17/50 (con't)	1235	4960	200	15	70.8	13	--	--	--			
	"	"	"	110	79.3	9	--	--	--			
	"	"	"	223	--	--	--	--	--			
	"	"	"	421	94.1	17	--	--	—			
	1309	--	400	15	97.6	8	--	--	--			
	"	"	"	110	84.4	8	--	--	--			
	"	"	"	223	--	--	--	--	--			
	"	"	"	421	92.9	7	--	--	--			
	1426	9270	30	15	72.6	13	90.5	11	--	270′	1	19°37.5′N
	"	"	"	447	95.0	4	91.4	3				75°32.5′W
Run 3 2/21/50	2044	--	30	15	84.8	4	77.0	9	--	220′	4	19°42′N
	"	"	"	53	90.6	8	78.7	9				75°13′W
	"	"	"	102	93.5	10	78.9	10				
	"	"	"	275	95.6	5	77.7	5				
			Repeat									
	"	--	30	15	91.8	6	--	--				
	"	10,010	200	15	88.3	6	80.5	7	12,850			
	"	"	"	53	90.8	8	82.9	10				
	"	"	"	102	96.7	6	83.3	5				
	"	"	"	275	94.7	9	82.0	8				
			Repeat									
	"	10,010	200	15	89.0	5	--	--				
	"	9810	300	15	91.3	10[1N]	77.6	24	12,503			
					MED 89.5							
	"	"	"	53	95.6	5	80.4	4				
	"	"	"	102	97.2	8	80.0	8				
	"	"	"	275	100.8	11[1N]	78.5	16				
					MED 100.0							
			Repeat									
		9810	300	15	97.7	10	--	--				
	"	"	"	275	103.2	4	--	--				
Run 5 2/24/50	1041	10,360	30	15	73.6	11	89.8	9	14,813	240′	2	19°32′N
	"	"	"	81	92.9	8	90.9	8				75°11′W
	"	"	"	152	87.8	9	88.7	9				
	"	"	"	330	96.4	12	90.1	12				
	1120	10,140	200	15	88.2	15	93.3	18	14,589	250′		
	"	"	"	81	88.4	8	93.7	7				
	"	"	"	152	95.0	10	93.1	10				
	"	"	"	330	100.4	17	92.6	16				
			Repeat									
	"	10,140	200	15	88.0	10	--	--				
	"	"	"	81	92.6	7	--	--				
	"	"	"	152	90.8	10	--	--		270′		
	1143	10,140	285	15	102.4	7	94.9	8	14,466			
	"	"	"	81	92.8	10	96.0	10				
	"	"	"	152	101.0	6	94.1	15				
	"	"	"	330	108.1	10	95.6	10				
			Repeat									
	"	10,140	285	152	97.4	9	--	--				
	1208	15,090	30	15	86.2	17	96.5	14	18,474	275′	2	19°32′N
	"	"	"	85	89.2	9	100.7	9				75°11′W
	"	"	"	158	89.8	8	96.5	7				
	"	"	"	338	107.5	20	99.1	21				

TABLE 1 (Continued)
Results of Tests, February and March 1950
Vicinity Guantanamo Bay

1	2	3	4	5	6	7	8	9	10	11	12	13
Run and Date	Time (Est)	Horz. Range (Yds)	Source Depth (Ft)	Hyd. Depth (Ft)	Direct Signal Loss, 1 Yd (db)	No. of Direct Pulses	Bottom Signal Loss, 1 Yd (db)	No. of Bottom Pulses	Slant Range Bottom Refl.	Depth of Channel	Sea State	Lat. & Long. of Recv. Ship
Run 5 2/24/50 (con't)	1223	14,840	200	15	86.6	22	93.1	18	18,260	295'		
	"	"	"	85	86.2	12	96.8	12				
	"	"	"	158	93.8	9	96.2	9				
	"	"	"	338	113.5	18^{1N}	96.1	17				
					MED 114.5							
	1247	14,710	340	15	91.1	11	90.0	11	18,326	310'		
	"	"	"	85	98.8	19	94.6	8				
	"	"	"	158	99.6	5	89.8	5				
	"	"	"	338	111.5	13^{1N}	90.8	13				
	"				MED 113.0							
Run 4 2/23/50	0819	15,260	30	15	81.9	29	86.1	26	18,722	270'	1	19°32.8'N
	"	"	"	90	91.6	11	87.1	15				75°11.6'W
	"	"	"	170	100.4	11	88.9	14				
	"	"	"	353	106.9	16	92.6	27				
			Repeat									
	"	15,260	30	15	81.3	3	--	--				
	"	"	"	90	96.3	3	--	--				
	"	"	"	170	102.0	3	--	--				
	"	"	"	353	109.6	7	--	--				
	0910	15,380	200	15	89.7	18	94.4	7	18,788	260'		
	"	"	"	90	85.5	24	94.2	19				
	"	"	"	170	108.4	11^{2N}	94.9	11				
					MED 108.0							
	"	"	"	353	111.6	22^{2N}	95.7	22				
					MED 111.0							
			Repeat									
	"	15,380	200	170	106.0	1	--	--				
	0923	15,730	325	15	96.2	8	88.7	8	19,052	260'		
	"	"	"	90	98.0	7	92.4	7				
	"	"	"	170	107.7	6	89.6	6				
	"	"	"	353	109.6	5	91.3	4				
Run 3 3/21/50	2226	22,140	30	46	92.8	4	--	--			4	19°42'N
	"	"	"	89	95.0	5	--	--				75°13'W
	"	"	"	252	93.0	19^{2X}	--	--				
	"	"	Repeat									
	"	22,140	30	46	92.3	14^{3X}	--	--				
	"	--	200	15	92.0	8	--	--				
	"	"	"	46	95.1	14	--	--				
	"	"	"	89	95.8	17	--	--				
	"	"	"	252	94.7	23	--	--				
Run 4 2/23/50	0947	25,160	30	15	88.5	25	106.6	25^{4N}	27,382	260'	1	19°32.8'N
							MED 107.1					75°11.6'W
	"	"	"	96	99.2	16	104.3	16				
	"	"	"	181	112.7	7	99.2	7				
	"	"	"	363	120.8	19^{1N}	100.5	19				
					MED 121.0							
			Repeat									
	"	"	30	15	--	--	94.9	6				
	"	"	"	96	98.0	2	93.6	2				
	"	"	"	181	100.0	2	95.1	2				
	"	"	"	363	120.2	5^{1N}	101.9	5				
					MED 119.0							

TABLE 1 (Continued)
Results of Tests, February and March 1950
Vicinity of Guantanamo Bay

1 Run and Date	2 Time (Est)	3 Horz. Range (Yds)	4 Source Depth (Ft)	5 Hyd. Direct (Ft)	6 Direct Signal Loss, 1 Yd (db)	7 No. of Direct Pulses	8 Bottom Signal Loss, 1 Yd (db)	9 No. of Bottom Pulses	10 Slant Range Bottom Refl.	11 Depth of Channel	12 Sea State	13 Lat. & Long. of Recv. Ship
Run 4	1110	25,270	200	15	105.0	10	100.3	10	27,497			
2/23/50	"	"	"	96	95.6	9	100.5	9				
(con't)	"	"	"	181	112.1	10	101.0	10				
	"	"	"	363	123.9	19^{8N}	102.5	16				
					MED 126.0							
	1116	25,440	350	15	104.5	10	102.0	10	27,662			
	"	"	"	96	110.5	8	103.8	9				
	"	"	"	181	109.9	11	104.5	11				
	"	"	"	363	119.3	9	104.8	9		260′	1	19°32.8′N
	1230	33,760	30	15	103.4	18	116.8	15^{6N}	35,313			75°11.6′W
							MED 115.8					
	"	"	"	94	107.1	11	115.8	9				
	"	"	"	177	123.6	9^{2N}	118.2	8				
					MED 123.0							
	"	"	"	360	>128.0	20^{16N}	120.4	19				
	1245	33,810	200	15	106.4	11	111.2	9^{2N}	35,530			
							MED 110.8					
	"	"	"	94	106.5	13	114.7	13^{1N}				
							MED 114.8					
	"	"	"	177	118.5	10^{2N}	117.6	9^{1N}				
					MED 119.0		MED 117.8					
	"	"	"	360	>124.0	14^{14N}	118.2	14^{1N}				
							MED 118.8					
	"	"	340	15	>118.0	3^{3N}	110,8	3^{1N}				
							MED 108.8					
	"	"	"	94	>120.0	16^{16N}	111.9	16				
	"	"	"	177	>123.0	8^{8N}	115.0	8				
	"	"	"	360	>125.0	14^{14N}	116.7	14				
			Repeat									
Run 8	0900	35,970	30	15	107.0	9	113.9	9	37,312	270′	2½	19°30.5′N
3/2/50	"	"	"	107	113.2	5	113.6	5				75°9.9′W
	"	"	"	212	127.0	6^{2N}	115.5	6				
					MED 128.5							
	"	"	"	405	126.5	12^{4N}	116.0	15				
					MED 127.0							
	0925	35,300	200	15	121.0	7^{3N}	116.5	6^{2N}	36,949			
					MED 123.0		MED 114.0					
	"	"	"	107	115.4	5	115.4	5				
	"	"	"	212	110.3	3	121.7	3^{1N}				
							MED 121.0					
	"	"	"	405	·127.8	12^{5N}	116.0	13				
					MED 128.0							
	0937	35,550	350	15	112.0	6	109.8	6	36,949			
	"	"	"	107	114.2	5	106.6	5				
	"	"	"	212	121.6	5	114.8	5				
	"	"	"	405	124.9	11	116.5	10				
Run 4	1330	43,300	30	15	113.0	7	116.2	7^{3N}	44,602	260′	1	19°32.8′N
2/23/50							MED 117.6					75°11.6′W
	"	"	"	97	114.5	16^{1N}	117.9	16^{2N}				
					MED 113.0		MED 117.8					
	"	"	"	184	124.4	5^{1N}	119.3	6^{1N}				
					MED 126.0		MED 117.8					

TABLE 1 (Continued)
Results of Tests, February and March 1950
Vicinity Guantanamo Bay

1	2	3	4	5	6	7	8	9	10	11	12	13
Run and Date	Time (Est)	Horz. Range (Yds)	Source Depth (Ft)	Hyd. Depth (Ft)	Direct Signal Loss, 1 Yd (db)	No. of Direct Pulses	Bottom Signal Loss, 1 Yd (db)	No. of Bottom Pulses	Slant Range Bottom Refl.	Depth of Channel	Sea State	Lat. & Long. of Recv. Ship
Run 4 2/23/50 (con't)	1330	43,300	30	367	>126.0	2^{1N}	122.3	2^{1N}				
							MED 120.3					
			Repeat									
	"	"	30	15	111.5	4	117.5	4				
	1402	43,190	200	15	124.3	22^{7N}	115.6	22	44,619			
					MED 125.0							
	"	"	"	97	126.0	8^{4N}	119.8	8				
					MED 126.5							
	"	"	"	184	>128.0	8^{7N}	123.5	8^{4N}				
							MED 121.3					
	"	"	"	367	>128.0	6^{6N}	>125.8	N				
	1418	42,930	340	15	108.0	9	107.9	9	44,042			
	"	"	"	97	105.0	6	106.6	6				
	"	"	"	184	115.7	6	110.9	7				
	"	"	"	367	>125.0	9^{9N}	113.9	8				
			Repeat									
	"	"	340	97	111.5	6	--	--				
	"	"	"	184	>125.0	4^{4N}	--	--				
Run 8 3/2/50	1040	44,700	30	15	109.8	4	116.5	2	45,724	270′	2½	19°30.5′N
	"	"	"	107	114.4	8	119.1	8				75°9.9′W
	"	"	"	212	121.5	8	120.6	9				
	"	"	"	405	>123.0	7^{7N}	122.4	7				
	"	44,780	200	15	119.2	9^{1N}	119.0	6	45,823			
					MED 119.0							
	"	"	"	107	117.4	5	118.1	5				
	"	"	"	212	>122.0	7^{4N}	119.6	8				
	"	"	"	405	>121.0	5^{5N}	122.3	6				
	"	44,980	355	15	>120.0	7^{7N}	116.4	7^{1N}	45,972			
							MED 114.5					
	"	"	"	107	117.8	8	112.5	8				
	"	"	"	212	125.3	7^{2N}	118.8	6				
					MED 124.0							
	"	"	"	405	>122.0	8^{8N}	124.4	9^{2N}				
							MED 124.5					
	1250	51,320	30	15	116.0	9	123.9	7^{3N}	52,042	270′	2½	19°30.5′N
							MED 122.8					75°9.9′W
	"	"	"	107	123.3	6	122.3	6^{2N}				
							MED 119.8					
	"	"	"	212	128.0	5	126.2	5^{1N}				
							MED 128.8					
	"	"	"	405	>124.0	6^{6N}	128.3	6^{1N}				
							MED 127.8					
	"	51,320	200	15	122.3	3	124.1	3	52,075			
	"	"	"	107	>122.0	9^{5N}	124.7	8^{3N}				
							MED 125.9					
	"	"	"	212	>124.0	5^{5N}	126.7	6^{1N}				
							MED 126.4					
	"	"	"	405	>124.0	6	128.1	7^{1N}				
							MED 127.8					
			Repeat									
	"	"	200	15	125.8	4^{1N}	>116.8	3^{2N}				
					MED 124.0							

TABLE 1 (Continued)
Results of Tests, February and March 1950
Vicinity of Guantanamo Bay

1 Run and Date	2 Time (Est)	3 Horz. Range (Yds)	4 Source Depth (Ft)	5 Hyd. Depth (Ft)	6 Direct Signal Loss, 1 Yd (db)	7 No. of Direct Pulses	8 Bottom Signal Loss, 1 Yd (db)	9 No. of Bottom Pulses	10 Slant Range Bottom Refl.	11 Depth of Channel	12 Sea State	13 Lat. & Long. of Recv. Ship
Run 8 3/2/50 (con't)	1307	51,270	360	15	122.8	8^{1N}	127.0	9^{3N}	52,075			
					MED 121.0		MED 129.8					
	"	"	"	107	>124.0	7^{4N}	124.7	7^{1N}				
	"	"	"	212	>124.0	5^{5N}	126.8	4^{2N}				
							MED 124.8					
	"	"	"	405	>124.0	7^{7N}	>118.8	7^{4N}				
	1140	55,430	30	15	>123.0	8^{8N}	>120.5	8^{7N}	56,165	270′	2½	19°30.5′N
	"	"	"	107	130.8	17^{6N}	>123.5	15^{11N}				75°9.9′W
	"	"	"		MED 133.0							
	"	"	"	212	>124.0	4^{4N}	>123.5	4^{4N}				
	"	"	"	405	>124.0	2^{2N}	>123.5	2^{2N}				
	1150	55,680	200	15	>124.0	6^{6N}	>121.5	6^{6N}				
	"	"	"	107	129.7	12^{2N}	133.5	12^{6N}				
					MED 128.0		MED 132.7					
	"	"	"	212	>124.0	5^{5N}	>123.5	5^{5N}				
	"	"	"	405	>125.0	4^{4N}	>124.5	4^{4N}				
	1201	55,770	355	15	>123.0	4^{4N}	>120.5	4^{3N}				
	"	"	"	107	125.4	11^{1N}	130.0	11^{5N}				
					MED 124.0		MED 133.5					
	"	"	"	212	128.7	6^{2N}	>122.5	6^{5N}				
					MED 129.0							
	"	"	"	405	>124.0	6^{6N}	>123.5	5^{5N}				

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